International Journal of Chemical Engineering and Applications, Vol. 16, No. 1, 2025

Purification of Biogas from Anaerobic Digestion of Food Processing Waste

António A. C. Barros[1,2,*], Estevão J. Nzinga[2], André B. Leite[3], Luciano da S. Lima[3], and Vinicyus R. Wiggers[4]

[1]Center for Research and Development (CpD) of Sonangol, Rua Rainha Ginga Nº29/31, Luanda, Angola
[2]Master's Degree in Chemical Engineering, Higher Polytechnic Institute of Technologies and Sciences (ISPTEC), Luanda, Angola
[3]Instituto Federal de Educação, Ciência e Tecnologia da Bahia (IFBA), Porto Seguro, Brazil
[4]Chemical Engineering Department, University of Blumenau, Blumenau, Brazil
E-mail: chivanga@gmail.com (A.A.C.B.); westjacinto@gmail.com (E.J.N.); andreburigo@ifba.edu.br (A.B.L.); lucianolima@ifba.edu.br (L.S.L.); vwiggers@furb.br (V.R.W.)
*Corresponding author

Manuscript received September 15, 2024; revised October 10, 2024; accepted October 17, 2024; published February 21, 2025

***Abstract*—Biogas is generated through the anaerobic digestion of organic biodegradable materials, such as food processing waste. However, its utilization is constrained by the presence of impurities, primarily carbon dioxide (CO_2), hydrogen sulphide (H_2S), and other gases found in tracer amounts. Physical and chemical absorption techniques can be employed to enhance the methane content of the gas above 97%. In this study, sodium hydroxide was used for biogas purification at concentrations of 2.5%, 5%, 7.5% and 10% in water. The paper investigated the effect of solvent concentration, solvent flow and gas flowrate on absorption and CO_2 and H_2S absorption. It was found that sodium hydroxide concentrations ranging from 2.5% to 5% exhibited favorable absorption rates and high removal efficiencies, greater than 95%, and depends on the fraction of the reagent used. The Process Provision II commercial simulator was employed for this study. The results were correlated with the mass transfer capacity during the absorption process, highlighting its potential application in industrial processes for purifying biogas derived from anaerobic digestion of organic material, particularly waste products.**

***Keywords*—absorption, mass transference, solubility, recovery**

I. INTRODUCTION

The acceleration of urbanization and industrialization processes, which involve the transformation of raw materials into high value-added products, necessitates the development of optimization studies to mitigate environmental impacts [1, 2]. Statistical data indicate that, on average, between 20% and 30% of Angola's national production of grains, fruits, and vegetables is wasted during the journey from farm to consumer. Data on the type and volume of residual organic matter produced in the industrial sector, communities, and agricultural waste are scarce in Angola. Such waste, classified as biomass with high nutritional value and potential for pollution, can result in significant public health problems if improperly disposed of in soils and water bodies, due to the leaching of compounds. Consequently, the transportation for final disposal and waste processing incurs significant costs that are often not accounted for [3].

One of the most suitable strategies in this context involves the application of environmental technologies for waste processing, aiming to harness the potential of residual biomass. This strategy focuses on the production of biogas and biofertilizers for use in electrical and thermal energy production processes, as well as agricultural production processes. Such technologies involve the use of biodigesters, which are fermentation chambers designed for the anaerobic or aerobic digestion of organic matter. Consequently, biodigesters represent a technological alternative for waste treatment and recycling, reducing pollution potential and sanitary risks that may compromise public health [4–6]. Biodigesters are devices employed for the production of biogas through the anaerobic decomposition of organic waste. They are essentially comprised of a tank, with or without an agitation system, where biomass is inserted for subsequent anaerobic digestion. Biodigesters are installed underground to minimize contact with atmospheric air and to reduce abrupt temperature variations during fermentative processes, thereby ensuring the stability of biogas production [7]. The use of biodigesters in the processing of residual organic matter not only minimizes improper waste disposal but also produces biogas and biofertilizer, the latter being used as an organic fertilizer in agriculture [8].

Anaerobic digestion aims to remove the polluting organic load, reduce pathogenic microorganisms, and produce more stable biogas and biofertilizers that are richer in assimilable nutrients and have better sanitary quality [9]. The digestion process involves a series of biochemical reactions resulting in the production of biogas, primarily composed of methane (CH_4) molecules, with concentrations between 60% and 70%, carbon dioxide (CO_2), and hydrogen sulfide (H_2S). According to Cazier *et al.* [10], biochemical and microbiological studies have divided the process of anaerobic decomposition of organic matter into four phases: (a) Hydrolysis stage; (b) Fermentative or acidogenic stage, (c) Acetogenic stage; and (d) Methanogenic stage.

During the hydrolysis stage, organic compounds, particularly proteins, fats, and carbohydrates, are decomposed into amino acids, fatty acids, and sugars. In the second stage, acidogenesis, bacteria transform the compounds produced in the hydrolysis stage into volatile fatty acids and other organic acids.

In the third stage of anaerobic digestion, acetogenesis, bacteria convert the acids produced during the acidogenesis phase into carbon dioxide (CO_2) and acetate through oxidation. The final stage of the process, methanogenesis, involves the conversion of acetate and carbon dioxide into methane, which accounts for 60% to 70% of the produced biogas [11]. The biogas generated can be used as fuel to produce electrical or thermal energy. The anaerobic digestion process entails the degradation and stabilization of organic

doi: 10.18178/ijcea.2025.16.1.833

matter, resulting in the production of methane, inorganic byproducts (CO_2 and H_2S), and biofertilizer (stabilized organic matter) (Eq. (1)).

$$\text{Organic Material} + H_2\ \text{Anaerobiose} \rightarrow CH_4 + CO_2 + NH_3 + H_2S + \text{Heat} \quad (1)$$

The efficiency of anaerobic digestion is strongly dependent on the operational conditions of the process, particularly pH, temperature, Hydraulic Retention Time (HRT), substrate composition, percentage of total solids, and the interaction between the involved microorganisms. These parameters directly affect the conversion rates and the quality of the produced biogas, especially regarding the methane fractions [12].

II. LITERATURE REVIEW

Biogas is characterized as a renewable energy source that has garnered significant scientific interest due to its content of short-chain hydrocarbon molecules, primarily methane (CH_4). The use of biogas in combustion processes aligns with the principles of decarbonization, as it results in reduced greenhouse gas emissions, proportional to the carbon dioxide absorbed during the photosynthesis processes of biomass production. As a biofuel, biogas is renewable and cost-effective, suitable for the production of heat, electricity, and chemical synthesis processes to produce high-value chemicals. The typical composition of biogas produced by anaerobic digestion is presented in Table 1.

Table 1. Normal biogas composition

Components	Concentration
Methane (CH_4)	50%–75% (v/v)
Carbon Dioxide (CO_2)	25%–45% (v/v)
Water (H_2O)	2%–7% (v/v)
hydrogen sulfide (H_2S)	20–20.000 ppm
Nitrogen (N_2)	< 2% (v/v)
Oxygen (O_2)	< 2% (v/v)
Hydrogen (H_2)	< 1% (v/v)

Adapted from Miotti [9].

The calorific value of biogas produced by anaerobic digestion is associated with the methane fraction present in the gas mixture, due to the high energy potential linked to the covalent bonds between the carbon and hydrogen atoms in methane's molecular structure. The calorific power of biogas is directly proportional to the methane content, as methane's covalent bonds provide significant energy potential [13, 14].

The most common utilization of biogas or other biofuel involves its combustion in energy generation systems to produce electrical energy or its use in direct combustion systems to produce heat [15–17]. Table 2 presents the energy equivalence of 1 cubic meter of biogas compared to the volume, in liters, of various types of fossil fuels.

Table 2: Biogas energy equivalent

1 m^3 of Biogas	Unities
Gasoline	0.61 liters
Kerosene	0.57 liters
Diesel	0.55 liters
GLP	0.45 Kg
Ethanol	0.79 liters
Firewood	1.538 Kg
Electrical Energy	1.428 Kw

Adapted by Holm-Nielsen *et al.* [17]

Thus, it can be observed that the higher performance of biogas is associated with the volume of fuel alcohol, corresponding to 79%, and gasoline, accounting for 61% of the consumption of 1 cubic meter of biogas. Therefore, to ensure the efficient use of biogas, purification processes should be implemented. These processes involve chemical absorption, based on the principles of mass transfer in absorption columns equipped with packings or trays. Physical and chemical absorption processes involve a strong interaction between biogas and an absorbent liquid, aimed at transferring impurities such as CO_2 and H_2S from the biogas to the solvent. This interaction relies on mass transfer phenomena by convection and molecular diffusion. The primary advantages of this method are the reduced costs associated with using water or reactants as solvents and the lower operational infrastructure costs. In this process, biogas is compressed and fed into the base of the absorption column, where it rises and interacts with the descending solvent, ensuring efficient mass transfer from the gas phase to the liquid phase [18, 19].

The main solutes are transferred to the solvent through dissolution in water and collected at the bottom of the absorption tower, as chemical reaction products. The residual product from the column base undergoes expansion to reduce solubility and recover the absorbed gases, enabling solvent recycling. The gas absorption process can achieve performance levels greater than 98%, depending on the throttling quotient, defined by the ratio between the solvent feed flow rate (S) and the gas feed flow rate (F).

When absorption rates are low, chemical absorption is implemented, involving reversible chemical reactions between the solute and the solvent, necessitating solvent regeneration to break these chemical bonds. Chemical solvents often include aqueous solutions of amines or alkaline salts such as sodium, calcium, or potassium hydroxides. For CO_2 removal, potassium carbonate (K_2CO_3) is used, with the gas introduced at the absorption column's base and the absorbing solution (20–30% by weight of K_2CO_3) injected at the top. CO_2 is released during regeneration by reducing the pressure in the absorption column, with residual CO_2 removed by injecting steam at the regeneration column's base [20].

Hydrogen sulfide (H_2S), an impurity with variable concentration in biogas, must be removed due to its corrosive effects on metal components of compressors, storage tanks, and engines, as well as its environmental impact. During combustion, H_2S converts to sulfur dioxide (SO_2), which reacts with water in the presence of light to produce sulfuric acid (H_2SO_4). This gas can be effectively removed using aqueous solutions of Fe/EDTA, as described in Eqs. (2) and (3) [21].

$$H_2S\,(g) \rightarrow H_2S\,(aq) \quad (2)$$

$$H_2S\,(aq) + 2Fe^{3+} + EDTA^{4-} \rightarrow S\downarrow + 2H^{+} + 2Fe^{2+}EDTA^{4-} \quad (3)$$

The catalytic solution of Fe/EDTA is synthesized in an inert atmosphere due to the complexities involved in its laboratory synthesis [22]. The biogas purification process typically targets the removal of carbon dioxide (CO_2) and hydrogen sulfide (H_2S), with methane (CH_4) being the primary desired component. When sodium hydroxide (NaOH)

is used as the absorbing solvent, specific chemical reactions (Eq. (4)) occur, as described by Náthia-Neves *et al.* [6].
For carbon dioxide absorption reaction:

$$CO_2(g)+2NaOH(aq) \rightarrow Na_2CO_3(aq)+H_2O(l) \quad (4)$$

The reaction involves the absorption of CO_2 by NaOH solution, resulting in the formation of Na_2CO_3 and water, as described in Eq. (5). This reaction effectively removes CO_2 from the biogas mixture.
For hydrogen sulfide absorption:

$$H_2S(g)+2NaOH(aq) \rightarrow Na_2S(aq)+2H_2O(l) \quad (5)$$

This reaction (Eq. (5)) is crucial for removing H_2S due to its toxic and corrosive properties, thereby purifying the biogas. Methane (CH_4), the valuable component of biogas for energy production, does not react with sodium hydroxide under normal conditions and remains unaltered during the absorption process. The overall goal of using NaOH in the absorption process is to remove CO_2 and H_2S from biogas, improving its quality for combustion and energy generation while retaining its methane content [23].

III. MATERIALS AND METHODS

For this work, studies were conducted using numerical simulation with Process Provision II, a macroscopic simulator that enables the evaluation of the operational performance of the absorption column, particularly in terms of mass transfer of the solute from the gas phase to the liquid phase (Fig. 1).

To evaluate the parametric relationships, particularly the ratio between the solvent flow rate and the gas feed flow rate (S/G), these parameters were used to determine the operating conditions that ensure the highest process performance in terms of solute recovery for a given number of trays.

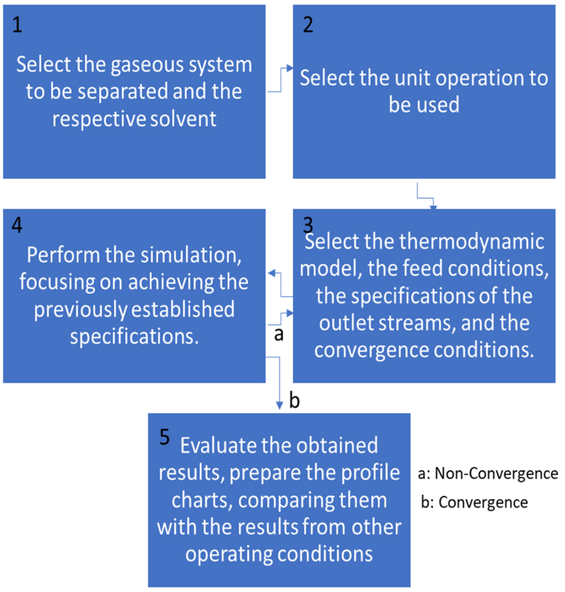

Fig. 1. Procedure used to simulate the process.

To better assess the performance of the process, sodium hydroxide solutions with four different concentrations were used as the solvent. The performance was evaluated based on the increased CH_4 recovery capacity, specifically the methane content in the top stream of the absorption column. The performance was measured using Eq. (6).

$$\%Rec = \frac{Y_T - Y_B}{Y_T} \cdot 100 \quad (6)$$

The data obtained from Eq. (6) led to the identification of operating conditions that optimize separation capacity through physical absorption. The resolution methods involved defining a thermodynamic model to calculate equilibrium constants, determining vapor pressure using the Antoine equation, and deriving equations to calculate enthalpies and excess Gibbs free energy. Given the reduced fractions of solutes in the gas stream, the equilibrium equation based on Henry's law was applied. Following these steps, feed conditions and corresponding specifications necessary for simulating convergence were established.

Additionally, operating efficiency was defined within specific ranges to ensure a comprehensive analysis of simulation results. The operation was simulated to gather data, which were evaluated in this study, focusing on the molar fraction profiles of the solutes under various operating conditions. Special attention was given to the concentrations of CO_2 and H_2S, as they influence the recovery capacity of these solutes in the biogas generated from anaerobic biomass digestion processes.

IV. RESULT AND DISCUSSION

The results of the numerical studies were presented through graphical analysis for various evaluated conditions, highlighting the importance of absorption processes in the quality of the obtained products and their impact on combustion quality, particularly in terms of reducing gas emissions. The study involved individually analyzing the recovery degree of each solute, measured through their respective mole fraction profiles, while exploring the effects of the solvent flow rate to gas feed flow rate ratio (S/F), for different concentrations of the reagent (NaOH). These analyses enabled the identification of the most suitable parametric relationship for the recovery degree of each solute, ensuring the purity of CH_4 (g) compatible with the specifications contained in the technical standards.

A. Recovery of H_2S

Hydrogen sulfide (H_2S) is one of the main components naturally present in raw natural gas. During combustion processes, H_2S reacts with water to form sulfuric acid. Due to its low solubility in water, studies of mass transfer processes with chemical reactions focus on absorption, involving appropriate reagents such as NaOH, as used in this study.

Fig. 2 illustrates the behavior of the H_2S fraction as a function of the S/F ratio for different concentrations of the reagent. The range of evaluated parameters was expanded to identify the conditions that ensure maximum solute recovery. For the four assessed operating conditions, better performance is observed for a NaOH concentration of 2.5%, which decreases with increasing concentration of this reagent. However, lower process performance is associated with a higher concentration of the reagent (10%), likely due to exceeding the limits established in the relationship between excess reagent and limiting reagent. For all evaluated cases, the S/F ratio that maximizes H_2S recovery lies between 3 and

4 (Fig. 2).

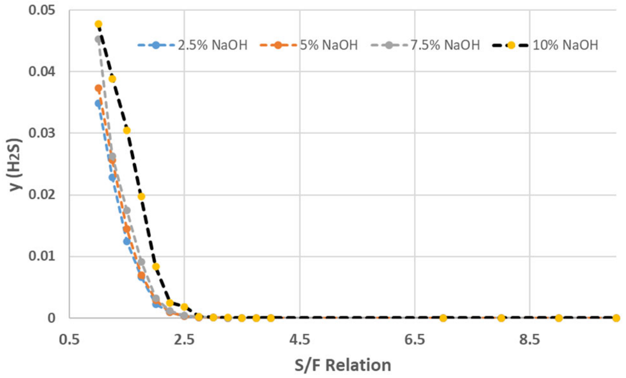

Fig. 2. Degree of H_2S recovery as a function of reactant mass and S/F ratio.

The performance depicted in Fig. 2 underscores the importance of optimizing solvent usage to minimize the production of industrial waste, which significantly impacts the environment. This necessitates the implementation of suitable effluent treatment stations for the purification of secondary streams involved in industrial processes.

B. Recovery of CO_2

Carbon dioxide (CO_2) is a gaseous chemical compound that contributes to the greenhouse effect and Earth's climate change. This gas negatively impacts combustion processes, leading to a reduction in energy efficiency. This is because part of the energy contained in biogas must be used to mitigate the effects associated with the presence of CO_2, thereby decreasing the overall efficiency of the process.

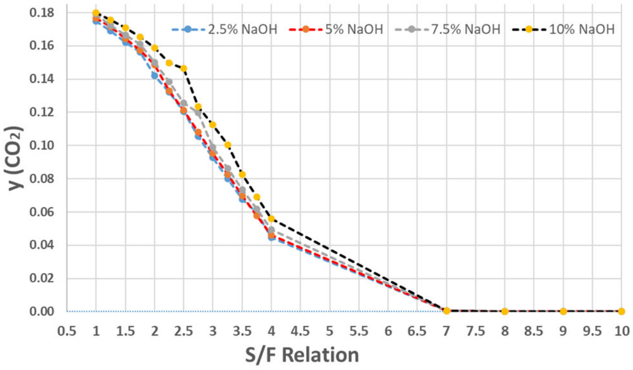

Fig. 3. Degree of CO_2 recovery as a function of reactant mass and S/F ratio.

A study was conducted on biogas purification, focusing on the recovery of CO_2, a solute with low solubility in water. The study involved chemical absorption simulation, using NaOH dissolved in varying proportions in water as the excess reagent and CO_2 as the limiting reagent. The results are presented in Fig. 3, for four different concentrations of the reagent and various values of the S/F ratio.

According to the data (Fig. 3), the process performance is more pronounced with reagent concentrations of 2.5% and 5% NaOH, up to an S/F ratio of 7. Values of the S/F ratio greater than 7 show the stability of the molar fraction of carbon dioxide evaluated in this work.

The performance associated with reduced reagent concentrations indicates the need for subsequent treatment processes to handle the lower volumes of reaction products. The S/F ratio with the highest performance observed in Fig. 3 correlates with the CO_2 levels produced in anaerobic digestion processes. These processes require intensified solvent flows to meet the demands of the biological conversions observed in anaerobic digesters.

C. Purification degree of CH_4

The reduction of solute content (H_2S and CO_2) observed in Figs. 2 and 3 leads to an increase in methane (CH_4) concentration, reaching the limits established by technical standards for the use of biogas in internal combustion systems. Fig. 4 illustrates the evolution of methane fractions with increasing S/F ratio and for different concentrations of the limiting reagent used in this study. It is noted that the S/F ratio of 7 exhibits the highest performance, which remains stable for subsequent values. However, at this S/F ratio (7), the highest molar fractions of methane were obtained with a reagent concentration of 10%. This condition is disadvantageous due to the pronounced need for significant volumes of reagents for the treatment of secondary streams in this process.

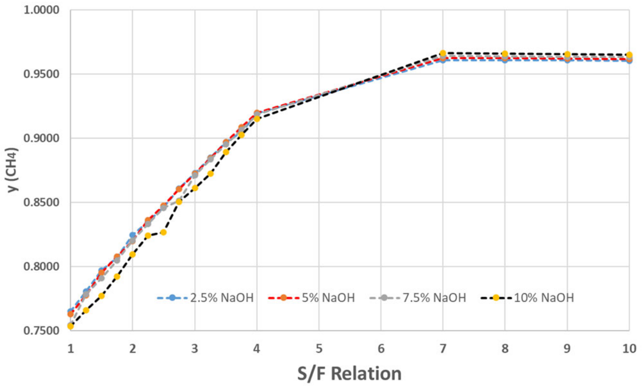

Fig. 4. Degree of purification of CH_4 as a function of reactant mass and S/F ratio.

D. Process Performance

Fig. 4 demonstrates that the process was most effective for reduced reagent concentrations (2.5%) up to an S/F ratio of 4. Beyond this ratio, the best performance was associated with the use of a reagent with 10% NaOH, up to the limit of the studied parameters. However, the study was conducted isothermally at a temperature of 30 °C. Evaluating the effect of temperature on the process performance is necessary to better define operating conditions that ensure qualitative improvement of this process.

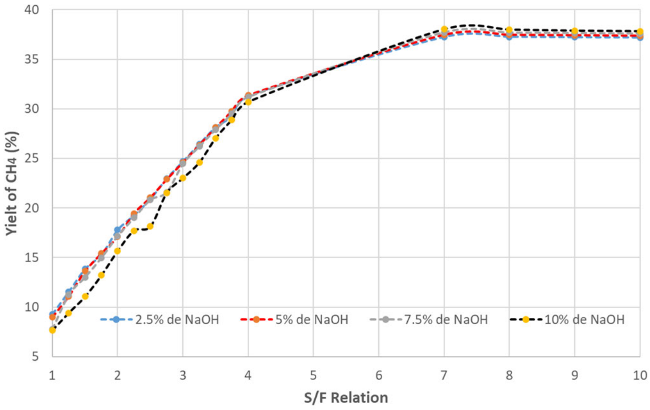

Fig. 5. Performance of CH_4 purification, as a function of reactant mass and S/F ratio.

E. Temperature Effect

Considering the process performance obtained with an S/F ratio of 4, a reagent concentration of 5%, and an operating temperature of 30 °C, the first two parameters (NaOH concentration and temperature) were fixed. The evolution of CH_4 concentration in the top stream of the absorption column was then evaluated for a temperature range between 10 °C and 60 °C.

The effects of reagent volatilization as a function of temperature were considered, and a reduction in CH_4 fractions in the top stream was observed, as shown in Fig. 6. To increase process performance, temperatures below 30°C are required to ensure high CH_4 content in the top of the absorption column, complying with international technical standards for using biogas as a biofuel in Angola's energy matrix. In absorption processes, temperature significantly impacts the solubility of gases in the absorbent solvent. As temperature increases, the solubility of CO_2 and H_2S in the solvent generally decreases. Additionally, temperature influences the kinetics of the absorption process. Lower temperatures, typically, slow down the rate at which CO_2 and H_2S are absorbed into the solvent, prolonging the contact time needed for efficient separation.

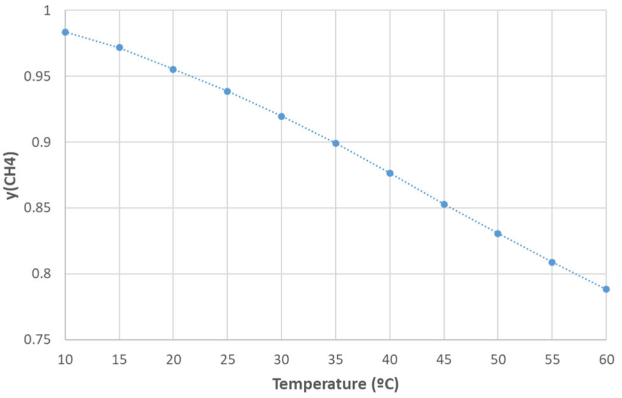

Fig. 6. Effect of temperature on the degree of CH_4 purification.

Operating at lower temperatures may require additional energy input for cooling, which could increase operational costs.

V. CONCLUSION

Based on the development of this study, the following conclusions can be drawn:

a) Sodium hydroxide, when used as a reagent in chemical absorption processes, demonstrates good performance in the simultaneous recovery of solutes such as hydrogen sulfide and carbon dioxide, even at low reagent concentrations;
b) The proposal to use this reagent in biogas purification processes focuses on cost minimization for physical absorption processes, which typically require two specific columns due to the absorption capacity of the physical solvents involved;
c) The innovation and contribution of this work lie in the need to implement chemical absorption processes as a strategy for the simultaneous recovery of solutes from biogas production through anaerobic digestion. In the pursuit of alternative energy sources, chemical absorption significantly reduces the costs of such processes;
d) The effects of temperature and the S/F ratio, combined with absorption parameters, result in greater mass transfer efficiency and ensure the optimization of industrial units, improving overall process performance;
e) Further studies should be conducted to obtain experimental data, at bench or pilot scale, to validate the results of this work and explore other reagents capable of maximizing absorption rates while reducing associated costs;
f) Therefore, this work highlights the importance of numerical studies in evaluating industrial processes, serving as a starting point for solving industrial problems, where the results demand high parametric sensitivity, requiring the use of appropriate tools.
g) Each component behaves differently along the absorption column, depending on the kinetics of the involved reactions and individual mass transfer rates.

NOMENCLATURE

a) Y_T: Gas mole fraction in the top of column;
b) Y_B: Gas mole fraction in the bottom of column;
c) %Rec: Recuperation;
d) EDTA: Ethylenediaminetetraacetic acid;
e) Fe/EDTA: Catalytic solution.

CONFLICT OF INTEREST

The authors declare that they have no financial or other interests that could influence the evaluation of this work. Furthermore, they state that they have no relationships with any individuals or entities that could compete with the interests of this scientific work. As such, the authors are solely focused on disseminating the scientific results in this important journal.

AUTHOR CONTRIBUTIONS

All the authors of this article engaged to the development of this work, more specifically: António A. C. Barros: Conceptualization, Writing, Editing, Methodology and Supervision; Estevão J. Nzinga: Methodology, Writing; André B. Leite: Methodology, Simulation, Review; Luciano da S. Lima: Simulation, Editing and Review; Vinicyus R. Wiggers: Editing and Review. All authors had approved the final version.

ACKNOWLEDGMENT

The authors of this work would like to express their sincere appreciation for the collaboration and support provided by the Post-Graduation Coordination and the Coordination of the Undergraduate Chemical Engineering Course at ISPTEC.

This work was supported by the Foundation for Research Support and Innovation of Santa Catarina State (FAPESC) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq no 302903/2023-2). Your dedication and assistance were instrumental in the development of this research.

We also thank the Pró-Reitoria de Pesquisa, Pós-Graduação e Inovação (PRPGI) of the Instituto Federal de Educação, Ciência e Tecnologia da Bahia (IFBA) for the financial support provided for the publication of this paper.

REFERENCES

[1] A. Karagiannidis, *Waste to Energy: Opportunities and Challenges for Developing and Transition Economies*, 1st ed. London: Springer, 2012

[2] K. Hobson, "The limits of the loops: critical environmental politics and the circular economy," in *Trajectories in Environmental Politics*, Routledge, 2022, pp. 158–176.

[3] K. Hobson, H. Holmes, D. Welch, K. Wheeler, and H. Wieser, "Consumption work in the circular economy: A research agenda," *Journal of Cleaner Production*, vol. 321, 128969, 2021. doi.org/10.1016/j.jclepro.2021.128969

[4] J. P. Rodrigues, A. C. A. Orrico, M. A. P. Orrico Junior, L. O. Seno, and L. C. Araújo, "Anaerobic co-digestion of swine manure and waste oil inclusion levels," *Eng. Agric.*, vol. 35, no. 4, pp. 657–664, 2015. https://www.scielo.br/j/eagri/a/cffwjVBVqgVpXNT4R5x9pmy/?format=html (in Portuguese)

[5] M. M. C. Rajivgandhi and M. Singaravelu, "Upgrading biogas to biomethane by physical absorption process," *International Journal of Agriculture, Environment & Biotechnology*, vol. 7, no. 3, pp. 639–644, 2014. doi: 10.5958/2230-732X.2014.01370.9

[6] G. Náthia-Neves, M. Berni, and G.Dragone, "Anaerobic digestion process: Technological aspects and recent developments," *Int. J. Environ. Sci. Technol.*, vol. 15, pp. 2033–2046, 2018. https://doi.org/10.1007/s13762-018-1682-2

[7] N. G. Paixão and V. D. Mateus, "Evaluation of the process of obtaining biogas from animal excrement," S*tudent Seminar on Academic Production*, vol. 16, 2018. https://revistas.unifacs.br/index.php/sepa/article/view/4900

[8] J. A. Galbiatti, A. D. Caramelo, F. G. Silva, E. A. B. Gerardi, and D. A. Chiconato, "Qualitative and quantitative study of biogas produced by substrates in batch-type biodigesters," *Brazilian Journal of Agricultural and Environmental Engineering*, vol. 14, no. 4, pp. 432–437, 2010. https://www.scielo.br/j/rbeaa/a/xYwqQcNLwQr6yZ4kTFk5sxs/?lang=pt&format=html (in Portuguese)

[9] P. D. S. Miotti, "The valorization and use of biogas in the agroindustry of Cacoal/RO," *Paula Duarte Silva Miotti—Cacoal/RO: UNIR*, 2016. https://core.ac.uk/download/pdf/294853741.pdf (in Portuguese)

[10] E. A. Cazier, E. Trably, J. P. Steyer, and R. Escudié, "Biomass hydrolysis inhibition at high hydrogen partial pressure in solid-state anaerobic digestion," *Bioresource Technology*, vol. 190, pp. 106–113, 2015. doi: 10.1016/j.biortech.2015.04.055

[11] G. M. B. Caldereiro, "Characterization of agro-industrial waste digestion in a continuous flow biodigester operated on a full scale," MS thesis, Environmental Technologies, Universidade Tecnológica Federal do Paraná, Medianeira, 2015. http://repositorio.utfpr.edu.br/jspui/handle/1/1277 (in Portuguese)

[12] L. L. T. Azevedo, "The economic viability of biodigesters in commercial pig farms," *Economics Notebooks Magazine*, vol. 15, no. 29, pp. 49–57, 2011. doi.org/10.46699/rce.v15i29.1641. https://bell.unochapeco.edu.br/revistas/index.php/rce/article/view/1641 (in Portuguese)

[13] M. Lisowyj and M. M. Wright, "A review of biogas and an assessment of its economic impact and future role as a renewable energy source," *Rev. Chem. Eng.*, vol. 36, pp. 401–421, 2020. doi.org/10.1515/revce-2017-0103

[14] C. A. de L. Chernicharo, R. M. Stuetz, C. L. Souza, and G. C. B. de Melo, "Alternatives for controlling odorous emissions in anaerobic reactors treating domestic sewage," *Eng. Sanit. e Ambient.*, vol. 15, no. 3, pp. 229–236, 2010. https://www.scielo.br/j/esa/a/gSDjZc8BMWxWLFFkCPJKJfk/?lang=pt (in Portuguese)

[15] K. Hagos, J. Zong, D. Li, C. Liu, and X. Lu, "Anaerobic co-digestion process for biogas production: progress, challenges and perspectives," *Renew Sustain. Energy Rev.*, vol. 76, pp. 1485–1496, 2017. doi.org/10.1016/j.rser.2016.11.184

[16] K. D. de A. Frigo, A. Feiden, N. B. Galant, R. F. Santos, A. G. Mari, E. P. Frigo, "Biodigesters: Their models and applications," *Acta Iguazu*, vol. 4, no. 1, pp. 57–65, 2015. doi: 10.48075/actaiguaz.v4i1.12528 (in Portuguese)

[17] J. B. Holm-Nielsen, T. A. Seadi, and P. Oleskowicz-Popiel, "The future of anaerobic digestion and biogas utilization," *Bioresource Technology*, vol. 100, no. 22, pp. 5478–5484, 2009.

[18] A. B. Leite, S. L. Bertoli, and C. Barros, "Antonio Andre. chemical absorption of nitrogen dioxide (NO_2)," *Engenharia Sanitaria e Ambiental*, vol. 10, pp. 49-57, 2005. https://doi.org/10.1590/S1413-41522005000100006.26 (in Portuguese)

[19] A. B. Leite, S. L. Bertoli, and C. Barros, and A. André. "Gas absorption process in minimizing air pollution," *Department of Chemical Engineering of the Regional University of Blumenau-FURB*, vol. 17, pp. 1–8, 2008. https://scholar.google.com.hk/scholar?hl=zh-CN&as_sdt=0%2C5&q=Processo+de+Absor%C3%A7%C3%A3o+de+Gases+na+Minimiza%C3%A7%C3%A3o+da+Polui%C3%A7%C3%A3o+Atmosf%C3%A9rica&btnG= (in Portuguese)

[20] A. Wellinger and A. Lindberg. (2000). Biogas upgrading and utilization. [Online]. Available: https://www.researchgate.net/publication/245587554_Biogas_Upgrading_and_Utilisation

[21] J. F. Demmink, A. Mehra, and A. A. C. M. Beenackers, "Absorption of hydrogen sulfide into aqueous solutions of ferric nitrilotriacetic acid: Local auto-catalytic effects," *Chemical Engineering Science*, vol. 57, no. 10, pp. 1723–1734, 2002. doi.org/10.1016/S0009-2509(02)00072-6

[22] M. S. Horikawa, F. Rossi, M. L. Gimenes, C. M. M. Costa, and M. G. C. Silva, "Chemical absorption of H_2S for biogas purification," *Braz. J. of Chem. Eng.*, vol. 21, no. 3, pp. 415–422, 2022. https://doi.org/10.1590/S0104-66322004000300006

[23] J. I. Huertas, N. Giraldo, and S. Izquierdo, "Removal of H_2S and CO_2 from Biogas by Amine Absorption," *Mass Transfer in Chemical Engineering Processes*, vol. 307, pp. 133–150, 2011. http://www.intechopen.com/books/mass-transfer-in-chemical-engineeringprocesses/removal-of-h2s-and-CO2-from-biogas-by-amine-absorption